Preliminary observations of global ocean mass variations with GRACE

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[1] Monthly estimates of the Earth’s gravitational field from the GRACE mission are used to construct a time-series of global mean ocean mass variations between August 2002 and December 2003. This time-series is compared to a mean climatology determined from satellite altimeter measurements of global mean sea level corrected for the steric variation. The GRACE observations show a seasonal exchange of water mass with the continents of the same magnitude (~8.5 mm) and phase (maximum in early- to mid-October) as the steric-corrected altimetry. This is one of the first direct validations over the ocean of the primary GRACE science mission to measure time-variable transports of water mass in the Earth system, and it suggests that GRACE data can be used to measure non-steric mean sea level variations which is important for climate change studies. INDEX TERMS: 1655 Global Change: Water cycles (1836); 1836 Hydrology: Hydrologic budget (1655); 4556 Oceanography: Physical: Sea level variations. Citation: Chambers, D. P., J. Wahr, and R. S. Nerem (2004), Preliminary observations of global ocean mass variations with GRACE, Geophys. Res. Lett., 31, L13310, doi:10.1029/2004GL020461.

1. Introduction

[2] It is known that the Earth’s oceans, atmosphere, and land exchange water mass as part of the hydrological cycle via precipitation, evaporation, freezing, melting, and runoff. Although the total amount of water in the Earth system is constant, the amount in any component (atmosphere, oceans, soil moisture, glaciers, ice sheets, etc.) can vary significantly over time. The ocean and continents are the largest reservoirs, with only a relatively small amount being stored in the atmosphere. When averaged globally, there is a large seasonal exchange of water mass between the oceans and land, which has been measured directly with satellite altimetry corrected with a climatological steric model [Chen et al., 1998; Minster et al., 1999; Cazenave et al., 2000]. Satellite radar altimeters observe the total sea level variation, including the signal caused by temperature and salinity fluctuations (the steric effect) and non-steric barotropic and mass variations. After removing the steric variation from the altimeter sea level measurements and averaging globally, the residual is interpreted as the eustatic, or mass variation.

[3] Although altimeter missions like TOPEX/Poseidon (T/P) and Jason-1 observe the total global mean sea level (GMSL) variation every 10-days, determining the global steric variation at the same frequency is impossible. There are not enough in situ measurements in a 10-day period to sample the global oceans; it is difficult enough to collect sufficient data in 1- or 5-year periods to compute global steric variations [Levitus et al., 2000]. Instead, the steric variation is computed from monthly average grids of temperature and salinity profiles determined from decades of in situ data, such as the World Ocean Atlas (WOA) climatologies [e.g., Stephens et al., 2002]. This limits one to studying only the seasonal water mass cycle in the oceans. Previous studies have all shown that the ocean mass variation is significant, with annual amplitudes between 7 and 9 mm of water, and a maximum in late-summer, early-fall [Chen et al., 1998; Minster et al., 1999; Cazenave et al., 2000].

[4] The GRACE Mission was designed to measure changes in the Earth’s gravity field caused by water mass moving among the components of the Earth system. A description of the mission and its present status can be found in Tapley et al. [2004]. In the following sections, we discuss the computation of the water mass time-series, and we compare the two calculations (GRACE and steric-corrected altimetry) to assess the ability of GRACE to observe the global water cycle.

2. Data Processing

2.1. Altimetry and Steric GMSL

[5] We use data from the TOPEX altimeter on T/P for January 1993 to July 2002, and data from the Jason-1 altimeter for August 2002 to December 2003, giving 11 years of continuous altimeter observations of global mean sea level along the same groundtrack. Besides applying the normal geophysical and atmospheric corrections, we include corrections for a drift in the TOPEX microwave radiometer and a new sea state bias model [Chambers et al., 2003a], and remove a global bias of 15 cm to align the Jason-1 data with TOPEX [Chambers et al., 2003b]. An inverted barometer (IB) correction is not applied to the data, since the IB model used to correct the altimetry is
2.2. GRACE

due to our longer altimetry time series, which better
et al. (278 similar to the previous estimates [variation (Figure 1). While our amplitude (8.8 mm) is
GMSL climatology from altimetry, there is a clear seasonal
the steric GMSL climatology is subtracted from the total
The average is area-weighted similar to the altimetry. When
averaging over the 11 values for January, February, etc.
first removing a bias and 11-year trend from the record, then
averaging over the 11 values for January, February, etc.

[6] The steric variation is computed from the most recent
World Ocean Atlas 2001 (WOA01) grids [Stephens et al.,
2002]. The steric variation at each grid point and month is
computed from changes in the ocean density field computed
from the temperature and salinity values to 1500 m depth
and an equation of state (see Jayne et al. [2003] for
formulation). The 1° maps of steric sea level anomalies are
then averaged over the oceans between ±66° latitude.
The average is area-weighted similar to the altimetry. When
the steric GMSL climatology is subtracted from the total
GMSL climatology from altimetry, there is a clear seasonal
variation (Figure 1). While our amplitude (8.8 mm) is
similar to the previous estimates [Chen et al., 1998; Münster
et al., 1999; Cazenave et al., 2000], our maximum phase
(278°) occurs approximately a month later. This is mainly
due to our longer altimetry time series, which better
averages through the large 1997–1998 ENSO event.

2.2. GRACE

[7] GRACE does not measure gravity field or mass
variations directly, but instead measures changes in range
between the two GRACE spacecraft. These range variations
are used to estimate a set of spherical harmonic coefficients
representing the gravity field each month. Thus, the GRACE
data represent a spatial averaging of the mass variations,
and not a point measurement. Although the time-variable
gravity field is estimated to spherical harmonic degree and
order 120 (wavelength ~300 km), the expected errors are
significantly larger than the time-variable signal except at
the longest wavelengths. Swenson and Wahr [2002] describe
a method to compute mean water mass variations over a
specific region using an averaging kernel that has a value of
~1 inside the region and ~0 outside the region, and
constructed to minimize the errors in the mass recovery.

We use this method to compute the ocean mass variations
by constructing an averaging kernel over the global oceans.
This is a slightly different averaging area than the coverage
of the altimetry and steric observations (~66°), and the
consequences are discussed in the next section. The mean ocean water mass is expressed in mm of equivalent
water thickness so that it directly corresponds to the non-
steric GMSL measurements from the altimetry and steric
observations.

[8] We use “monthly” sets of the gravity coefficients
distributed by the GRACE project via PODAAC to
the Science Team for August–November, 2002, February–
April/May 2002 is available but is not used because the
data processing may not have handled several in-flight
activities that occurred during the time-period (S. Bettadpur,
personal communication, 2004) and it stands alone in
time without nearby solutions. The coefficients are not
necessarily estimated over exact monthly intervals due to
data outages and the groundtrack of the GRACE
satellites. The time stamp we assign to the GRACE average is the
mid-point of the exact time interval used to compute the
coefficients. GRACE is sensitive to the water mass variati-
ons in the ocean, land, and in the atmosphere below it.
However, a model of the atmospheric gravity signal deter-
dined from the ECMWF model as well as a barotropic
model forced by ECMWF winds and pressure is used in the
GRACE processing as part of the background force model,
along with other effects such as ocean tides, solid earth
tides, and others. Thus, the gravity field coefficients are the
observed variation relative to these background models.
If the models are accurate, then the signals have been
effectively removed, and the GRACE products measure
the time-variable gravity excluding the atmosphere, tides,
etc. If the models are not accurate, then the GRACE
data will contain the true variation corrupted by the model error.
An important part of the GRACE calibration/validation
effort is to assess if there are indications of errors in the
background force models.

[9] The barotropic model used in the processing is known to
have problems at monthly periods (V. Zlotnicki, personal
communication, 2003), as it is designed mainly to predict the
ocean’s barotropic variability at periods of a few days. Thus,
one should restore the monthly average of the model heights
to any maps determined from the GRACE fields. However,
the barotropic model is mass conserving, so that a global
average of the model output is always zero; water mass is
just exchanged within the model so there is no globally
average error, only local ones. We have confirmed that the
average of the model used for GRACE is approximately
zero. Thus, the GRACE average ocean mass variation
calculation is not affected by the barotropic model.

[10] The GRACE data are not corrected for the pole tide
over the ocean, but the altimetry is. So to be consistent, we
apply a pole tide correction to the GRACE results using the
same model used for the altimetry [Wahr, 1985]. We also
add back the secular rates for the degree 2 terms that were
removed as a background model in the GRACE processing,
since this is not done in the altimetry. The GRACE monthly
gravity field models do not include estimates of the degree 1
gopotential coefficients, which describe the movement of
the Earth’s center-of-mass in an Earth-fixed reference frame.
The GRACE measurements include degree 1 terms. (the geocenter), since the GRACE measurements are relatively insensitive to these long-wavelength gravity variations, and the GRACE frame of reference is chosen to be the instantaneous geocenter. However, including degree 1 terms is important if one is looking at just one component of mass variability, since the geocenter variations arise from transporting mass among and within the ocean, land, and atmosphere [Wahr et al., 1998]. Since we are interested in using GRACE to compute an independent, gravity-based estimate of the total water mass variability in the ocean, we add degree 1 terms to the GRACE coefficients instead of removing the corresponding signal from the altimetry. We adopt annual estimates of the geocenter motion from Chen et al. [1999] and convert them to degree 1 gravity coefficients. We re-compute the water mass variations including these degree 1 terms and compare the differences.

3. Discussion of Results

[11] Figure 1 shows the time-series of ocean mass variations measured directly by GRACE without the geocenter estimates, along with that derived from the steric-corrected altimetry. Figure 2 shows the same steric-corrected altimetry variation, but the GRACE measurements include the degree 1 estimates. The time-series have been arbitrarily biased so that the mean of an annual sinusoid is zero. Note that the GRACE measurements are the average over a specific month in a specific year (e.g., November, 2003), while the altimetry + steric measurements have been averaged over many years (e.g., mean of many Novembers). Although there are only 14 GRACE observations, the GRACE and steric-corrected altimetry measurements are in good agreement. There is a peak in late-Summer, early-Fall in both 2002 and 2003, as well as a minimum in late-Winter early-Spring of 2003. By comparing Figure 2 to Figure 1, it is clear that the GRACE observations agree more closely with the steric-corrected altimetry + steric measurements than the GRACE and steric-corrected altimetry overlap in every case. Thus, the GRACE observations are entirely consistent with the mean seasonal ocean mass variation related to the global water cycle. Deviations are as likely to be caused by real interannual variations as by errors in the GRACE data.

[13] We have fit an annual sinusoid to both the GRACE and steric-corrected altimetry time-series in Figures 1 and 2. The sinusoid is defined so that the phase represents the time of the maximum from January 1. Table 1 lists the estimated amplitude and phase, along with the formal errors, which take into account the error bars and the reduced sampling of the GRACE measurements. The difference in amplitudes is 1.3 mm if degree 1 terms are not included with GRACE, but only 0.1 mm if geocenter variations are included. The phase, however, does change slightly when degree 1 variations are included, but within expected errors, and well within the sampling (1 month = 30°). If the GRACE data are averaged only between ±66°, neither the amplitude nor phase change significantly (Table 1). This indicates that there was no significant error in the altimetry - steric measurements due to non-global sampling, which was uncertain before. This is the first validation that GRACE is observing real ocean mass variations, at least on very large scales.

[14] Several previous studies of the seasonal ocean mass variability have examined closing the water mass budget by using the outputs of climate and hydrology models over land, since the average of the land + atmosphere water mass signal should be exactly out of phase with the ocean mass variation [Chen et al., 1998; Cazenave et al., 2000; Milly et al., 2003]. The results of the previous studies are reproduced in Table 2. Overall, the agreement with the GRACE results is quite good, although there are still significant differences in both the amplitude and phase that likely reflect errors in the hydrologic models. This study, therefore, also validates the accuracy of the steric-corrected altimetry observation of the mean seasonal ocean mass variation, and further supports that there are still discrep-

Table 1. Estimated Annual Amplitude and Phase of Global Ocean Mass Variations From This Study

<table>
<thead>
<tr>
<th>Measurement Source</th>
<th>Amplitude (mm)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steric-corrected altimetry</td>
<td>8.5 ± 0.7</td>
<td>278 ± 5</td>
</tr>
<tr>
<td>GRACE (no degree 1)</td>
<td>7.2 ± 1.1</td>
<td>284 ± 8</td>
</tr>
<tr>
<td>GRACE (degree 1)</td>
<td>8.4 ± 1.1</td>
<td>266 ± 8</td>
</tr>
<tr>
<td>GRACE (degree 1), ±66°</td>
<td>8.6 ± 1.1</td>
<td>265 ± 8</td>
</tr>
</tbody>
</table>

*Errors are formal errors based on the individual error bars and number of points in the time-series. Phase is defined in degrees from January 1 using a cos(wt-phi) definition.

Table 2. Annual Amplitude and Phase of Global Ocean Mass Variations Determined From Hydrology Models or GPS

<table>
<thead>
<tr>
<th>Measurement Source</th>
<th>Amplitude (mm)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen et al. [1998] Model 1</td>
<td>5.9</td>
<td>231</td>
</tr>
<tr>
<td>Chen et al. [1998] Model 2</td>
<td>8.9</td>
<td>302</td>
</tr>
<tr>
<td>Cazenave et al. [2000]</td>
<td>9.0</td>
<td>250</td>
</tr>
<tr>
<td>Milly et al. [2003] LaD</td>
<td>9.7</td>
<td>241</td>
</tr>
<tr>
<td>Milly et al. [2003] ISBA</td>
<td>9.4</td>
<td>260</td>
</tr>
<tr>
<td>GPS Loading [Blewitt and Clarke, 2003]</td>
<td>7.6</td>
<td>234</td>
</tr>
</tbody>
</table>

*Phase is defined consistently with Table 1.
Differences could also be explained by real interannual data of about 1–2 mm of water thickness on global scales. Our analysis corroborates the error estimates for the monthly GRACE magnitude, but is different in phase by 0.1 mm and the difference in phase is only 12°. Our analysis corrected for a steric variation. The two methods observe nearly the same seasonal signal once we correct for reference frame differences. The difference in amplitude is 0.1 mm and the difference in phase is only 12°. Our analysis corroborates the error estimates for the monthly GRACE data of about 1–2 mm of water thickness on global scales. Differences could also be explained by real interannual variations measured by GRACE.

Although the determination of the mean seasonal ocean mass variation is not a unique result from GRACE, we expect that GRACE in the near future will contribute important new information to the Earth’s global water cycle. For example, while the seasonal signal of the ocean mass variability can be determined accurately from altimetry and a steric model, it is difficult to obtain interannual variations due to the scarcity of ocean temperature and salinity observations. There is no reason to believe that GRACE should measure the low-frequency variations less accurately than the seasonal, although part of the long-term signal will be contaminated by post-glacial rebound (PGR). However, the use of a long-enough record and PGR models might allow us to determine low-frequency eustatic sea level change directly for the first time, which will be an important constraint on models used to predict global climate change. By combining satellite altimetry (which measures steric + eustatic variations) with GRACE (eustatic), the difference will also reveal the sea level change due to ocean heating. Understanding the relative contributions of steric and eustatic changes to sea level rise is an important goal of sea level change science.

Additionally, GRACE observes time-variable mass over the continents. Preliminary calculations made over large continental discharge basins suggest that the accuracy of the GRACE measurements is at the level of a cm or less of water thickness [Wahr et al., 2004]. Over larger continental regions, the accuracy will improve. Thus, in the near future we will be able to utilize GRACE alone to quantify how mass is exchanged between the continents and oceans, without having to rely on a combination of data and models, each with differing accuracies.

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References


